REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
06-03-2006	Final Report	16 February 2005 - 16-Feb-06

4. TITLE AND SUBTITLE

Analysis and Coding for Multiple-Access Channels

5a. CONTRACT NUMBER
FA8655-05-1-3017

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 821 BOX 14
FPO 09421-0014

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Grant 05-3017

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The most important communication channels were investigated in the situation of multiple users. These models do not assume any central intelligence there is no coordination between the transmitters, so fit to the usual conditions of an ad-hoc or sensor network. Better bounds on the minimum code word length and efficient code constructions were achieved for the scenarios, when many independent, partially active transmitters are communicating over a shared medium. These techniques can be applied in the usual code division multiple access (CDMA) situations where time and frequency resources can be utilized in one continuous domain throughout the entire communication system. Neither CDMA, nor the recently used random access protocols for conflict resolution utilize the full power of the channels. Efforts were made to obtain better bandwidth throughputs between the transmitters, to fit to the usual conditions of an ad-hoc network.

15. SUBJECT TERMS
multi-user communication, multiple access channels, random access, information and coding theory, CDMA , EOARD

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Final Report on
”Analysis and Coding for Multiple-Access Channels”
ONR & AFOSR Grant FA8655-05-1-3017

This project is essentially a continuation of a one sponsored by ONR starting in 2004. In this report we summarize our work during the recent project only, so we cite here only our **new articles** and **our book**. To see the previous results please click here. [http://www.szit.bme.hu/~gyorfi/ONR/]

Introduction

Mobile communication facilities have become commonplace in many parts of every-day life. Almost all existing communication links at present could be replaced by cordless links. The benefits of such replacement e.g., mobility, flexibility, reduced installation costs are enormous. The ultimate goal for the civilian sector is to have a Universal Mobile Tele-communications System (UMTS). UMTS applies code division multiple access (CDMA) techniques, where time and frequency resources can be utilized in one continuous domain throughout the entire communication system. The number of users and percentage of the common medium a user can occupy is widely scalable, and there is a trade-off between these quantities. More active users appear simply as increased system-noise. Nowadays the CDMA systems, e.g., the 3G mobile telecommunication systems are extremely poor in channel usage efficiency. Their data rates are just a small fraction of the information-theoretic capacity. This is because they have to deal with channel errors, synchronization, and most importantly, be-cause we do not have a fundamental method yet to achieve full capacity. Even the mathemati-cal bases are still quite unexplored. Based on strong and wide theoretical results, future tech-nicians will be able to build communication systems utilizing the channel at a much higher rate.

In the background the life is not so nice. There are few things in nature more unwieldy than the power-limited, space-, time- and frequency-varying wireless channel. Yet there is great reward for engineers who can overcome these limitations and transmit data through such harsh environments. The explosive worldwide growth of personal communication services through the 1990s is a testament to the business opportunities that result from conquering the wireless channel. However, given the emergence of newer wireless systems that require more and more bandwidth, the task of conquering the wireless channel is becoming more difficult. This task requires a thorough theoretical background in wireless channel modeling (e.g., in-formation, coding and queuing theory). The major difficulty which faces radio communica-tion is the limited available frequency spectrum. The need for efficient spectrum utilization is essential.

Results and discussion

In this project we have investigated the most important deterministic channels. We achieved better bounds and efficient constructions for codes for multiple access scenarios, when many independent, partially active users are communicating over a shared medium, e.g., a frequency band. In general, a multiple access code should be able to detect the set of active users, synchronize their code words and decode their messages. If only the detection task is to be solved then we are speaking about the signature coding problem.

Book

We are preparing an information-theoretic study, a book of about 250 pages on some channel models. It is 95% ready. [PDF]

- L. Györfi, S. Győri, B. Laczay, M. Ruszinkó: Lectures on Multiple Access Channels
  - Chapter 1. Introduction
  - Chapter 2. OR channel: synchronous access
  - Chapter 3. OR channel: asynchronous access
  - Chapter 4. Collision channel
  - Chapter 5. Slow frequency hopping
  - Chapter 6. Collision channel with ternary feedback
  - Chapter 7. Multiple access adder channel
  - Chapter 8. Collision channel with known collision multiplicity
  - Chapter 9. Euclidean channel
  - Appendix A. Linear codes
  - Appendix B. Probability
  - Bibliography

The target of our book is the investigation of multiple access channel schemes. We summarize the results concerning the most important deterministic channels: e.g., OR channel, adder channel, collision channel and slow frequency hopping.

Papers

- M. Csűrös, M. Ruszinkó: Single-user tracing and disjointly superimposed codes. *IEEE Transactions on Information Theory*, 51(4):1606-1611, 2005. [PDF]
  We investigate the zero-error capacity region of r-out of T user multiple access OR channel. Suppose that T users share a common channel. A binary vector of length n is associated to each user. A user transmits its vector of length n if it is active, otherwise it does not. It is assumed that the transmission is bit and block synchronized. In the classical framework of superimposed coding, the receiver has to be able to identify the set of *all* active users from the output vector of the channel. Here we investigate the case when the receiver has to be able to identify *just one* user out of at most r active ones. A practical motivation for studying r-single user tracing codes rises from applications of combinatorial designs in genomics.
- A. Frieze, R. Martin, J. Moncel, M. Ruszinkó, C. Smyth: Identifying Codes in Random Networks. *IEEE International Symposium on Information Theory,* Adelaide, Australia, September 4-9, 2005, pp. 1464-1467. [PDF]
  In this paper we deal with codes identifying sets of vertices in random networks, that is l-identifying codes. These codes enable us to detect sets of faulty processors in a multiprocessor system, assuming that the maximum number of faulty processors is bounded by a fixed constant l. 1-identifying codes or simply identifying codes are of special interest. For random networks we use the model $G(n,p)$, in which each one of

the possible edges exists with probability p. We give upper and lower bounds on the minimum cardinality of a l-identifying code in a random network, as well as threshold functions for the property of admitting such a code. We derive existence results from probabilistic constructions. A connection between identifying codes and superimposed codes is also established.

- L. Györfi, S. Győri: Analysis of Collision Channel with Asynchronous Access. *IEICE Transactions on Fundamental of Electronics, Communications and Computer Sciences*, vol. E88-A, no. 10, pp. 2878-2883, 2005. [PDF]
  A multiple-access collision channel without feedback is considered. The traffic is in the form of packets taking values from a finite input alphabet. We are looking for codes and protocol sequences of users of minimum length such that from the output of the channel it can be determined which users were active and what they sent. Previously, Bassalygo and Pinsker solved this problem for binary packets. Using of non-binary packets commonly arises in practical communication (with non-binary packets the design of codes and decoding can be systematic and efficient). We prove that the same utilization can be reached as with binary packets, even if asynchronous access is allowed for the users.
- S. Győri: Coding for a Multiple Access OR Channel: a Survey. *Discrete Applied Mathematics* (in print). [PDF]
  This previously written survey on the multiple access OR channel is accepted for publication by the DAM. We summarize the results of Eastern (Dyachkov, Erdős, Frankl, Füredi, Györfi, Rödl, Ruszinkó, Rykov, T. Sós, Vajda, Zeisel, Zinoviev) and Western scientists (Berlekamp, Dorfman, Du, Ericson, Hwang, Justesen, Linial, Sterrett, Wolf) in the last two decades. Besides joining various results we strive for the homogeneous discussion of the topic. Many practical applications of communication via an OR channel are mentioned: login of new users into a mobile telecommunication system, collecting of measuring data, sending packets without error correction, alarming, monitoring, non-adaptive group testing, file retrieval system.
- L. Györfi, S. Győri: Analysis of Tree Algorithm for Collision Resolution. *International Conference on the Analysis of Algorithms*, Barcelona, Spain, June 6-10, 2005, pp. 355-362. [PDF]
  We consider the multiple-access collision channel with ternary feedback. An unlimited number of users are allowed to transmit packets of a fixed length whose duration is taken as a time unit and called slot. The destination for the packet contents is a single common receiver. Senders of different packets cannot exchange information. When two or more users send a packet in the same time slot, these packets collide and the packet information is lost, i.e., the receiver cannot determine the packet contents, and retransmission is necessary. However, all users, also those who were not transmitting, can learn the story of the previous time slot from the ternary feedback. For the collision resolution tree algorithm introduced by Capetanakis, Tsybakov and Mikhailov we show that the sequence of expected collision resolution time given the collision multiplicity and its Poisson transform does not converge but oscillates asymptotically. The amplitude and the frequency of the oscillation is also given.
- S. Győri: Signature coding for OR channel with asynchronous access. *IEEE International Symposium on Information Theory*, Adelaide, Australia, September 4-9, 2005, pp. 2040-2044. [PDF]
  In this paper the problem of signature coding for multiple access OR channel is considered, where the set of active users has to be determined from the output vector of the channel. Signature coding was considered in the literature only for synchronous access, when the active users begin to transmit their code words at the same time. We

prove that the best known upper bound on the minimum code length (given by Dyachkov and Rykov) is valid for the case of asynchronous access, too.

- S. Győri: Bounds on signature coding for fast frequency hopping with asynchronous access. *IEEE ITSOC Information Theory Workshop on Coding and Complexity*, Rotorua, New Zealand, August 29-September 1, 2005, pp. 63-67. [PDF]
  Signature coding for fast frequency hopping channel is studied, where the bandwidth is partitioned into frequency subbands. A frequency hopping pattern is assigned to each user that specifies the sequence of frequency subbands in which the user can transmit a sine waveform during a time slot. Partial activity is considered where only a small fraction of the potential users may be active simultaneously. We prove that in frame asynchronous case the upper bound on the minimum code length via random coding is asymptotically the same as in the case of synchronous access.
- B. Laczay, M. Ruszinkó: Multiple user tracing codes. *IEEE International Symposium on Information Theory*, Seattle, USA, July 9-14, 2006 (submitted). [PDF]
  In this paper we extend the so called single user tracing codes for multiple users. This way we manage to generalize previous results of famous scientists, e.g., N. Alon and V. Asodi. We fill up the gap between binary superimposed codes and single user tracing ones. Similar codes were used to identify the genome of Honey Bees and they are also useful in large scale search problems. The whole line of research also point forward achieving higher throughput over certain communication channels.

PhD Thesis

- S. Győri: *Multiple Access Channels.* Budapest University of Technology and Economics, Budapest, Hungary, 2005. [PDF]
  This Thesis summarizes some recent results on OR channel, collision channel, fast frequency hopping and random access, based on the journal and conference papers of the author written between 2002 and 2005.

Impact of our work

An important impact of our results is hosting the NATO Advanced Study Institute on Coding and Analysis of Multiple Access Channels, which will be held from 26 August – 5 September, 2006, in Budapest, Hungary, to be organized by L. Györfi.

As it was expected CDMA is one practical solution to the rapidly growing multiple-user communication needs. The systematic presentation of this topic in a book will hopefully get attention when new generation of sensors and ad-hoc networks will start to emerge. We summarized the relevant literature on information theory, probability theory and statistics, too. Among the citations there are many Hungarian and Russian results, moreover there are also results from the widely unknown mathematical literature, e.g., extremal set theory, statistical design, combinatorial design, algebraic methods, probabilistic methods.

We also presented and published our results at the most relevant forums of information theory. These facilitate efficient testing, user identification, information transfer, smaller code length and faster decoding.

Military impact

The CDMA schemes do not assume any central intelligence, there is no coordination between the transmitters, so fit to the usual conditions of an ad-hoc network, therefore CDMA is ideal for military applications.

In the recent Iraq situation the US commanders had a bandwidth higher by one magnitude than that was in the first Gulf War (cf. David Talbot: How Technology Failed in Iraq, Technology Review, November, 2004). In contrast, the capacity of human information processing was, is and will always be very limited. Therefore the extraction of the *relevant* information from the sensor network is the main bottleneck. We believe that the detection and recognition should be made in the sensors on the spot, and they should initiate information transmission only in cases when some detection or recognition has occurred. This would make the human information processing much easier and therefore more efficient. This communication situation is just the model of interest to us in our research: how to use a common multiple access channel serving a huge population of sensors if in a given time instant, only a small fraction of the sensors are active (the triggered ones). Superimposed codes are designed for exactly such models and this is the focus of our work.

Conclusion

We believe that the theoretical results we obtained in long run will lead to new real-life applications. We appreciate very much the support of ONR and AFOSR, and hope that we will be able to continue this research.